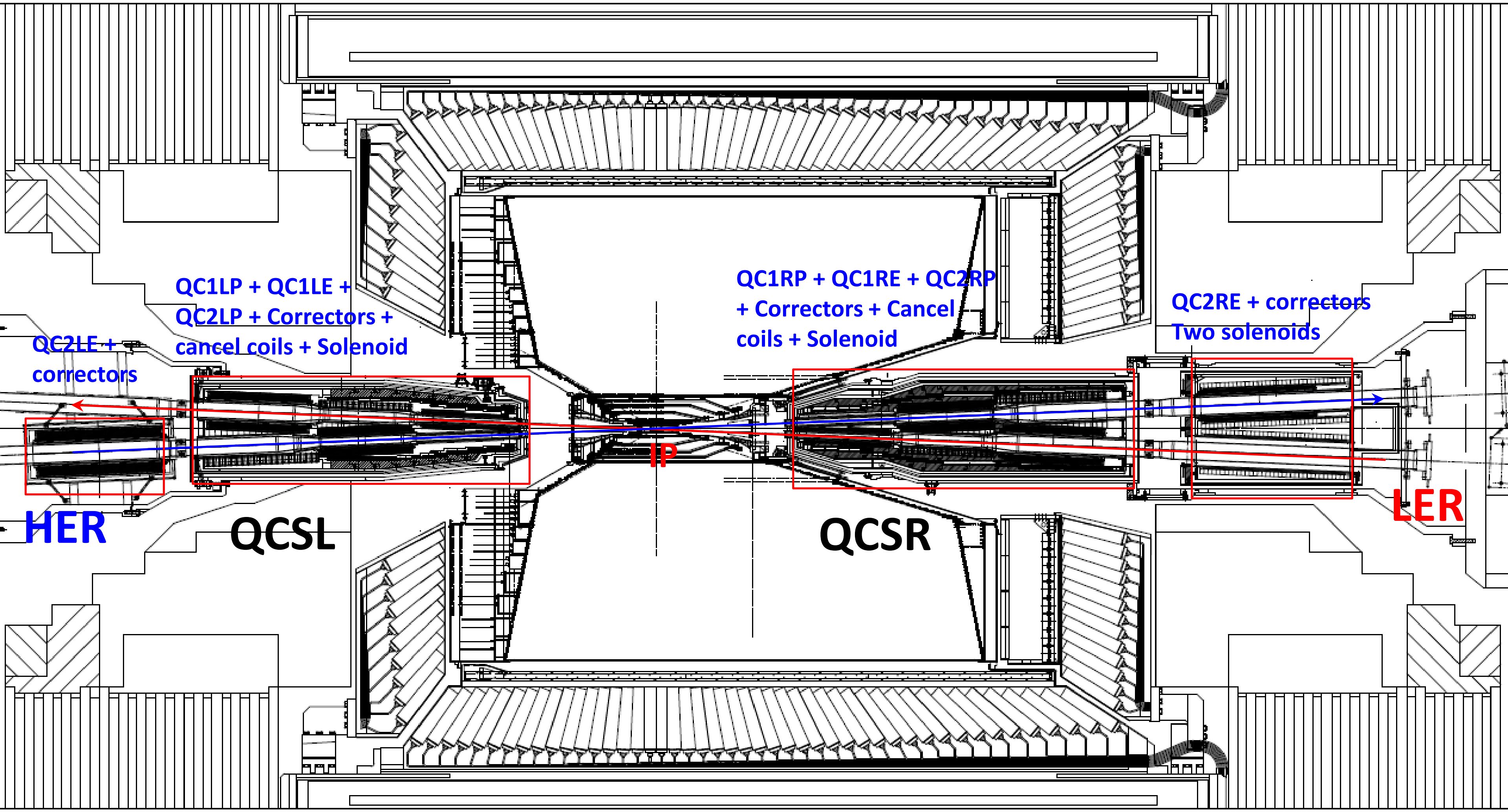
Superconducting Magnets for SuperKEKB Interaction Region

Norihito Ohuchi

Contents

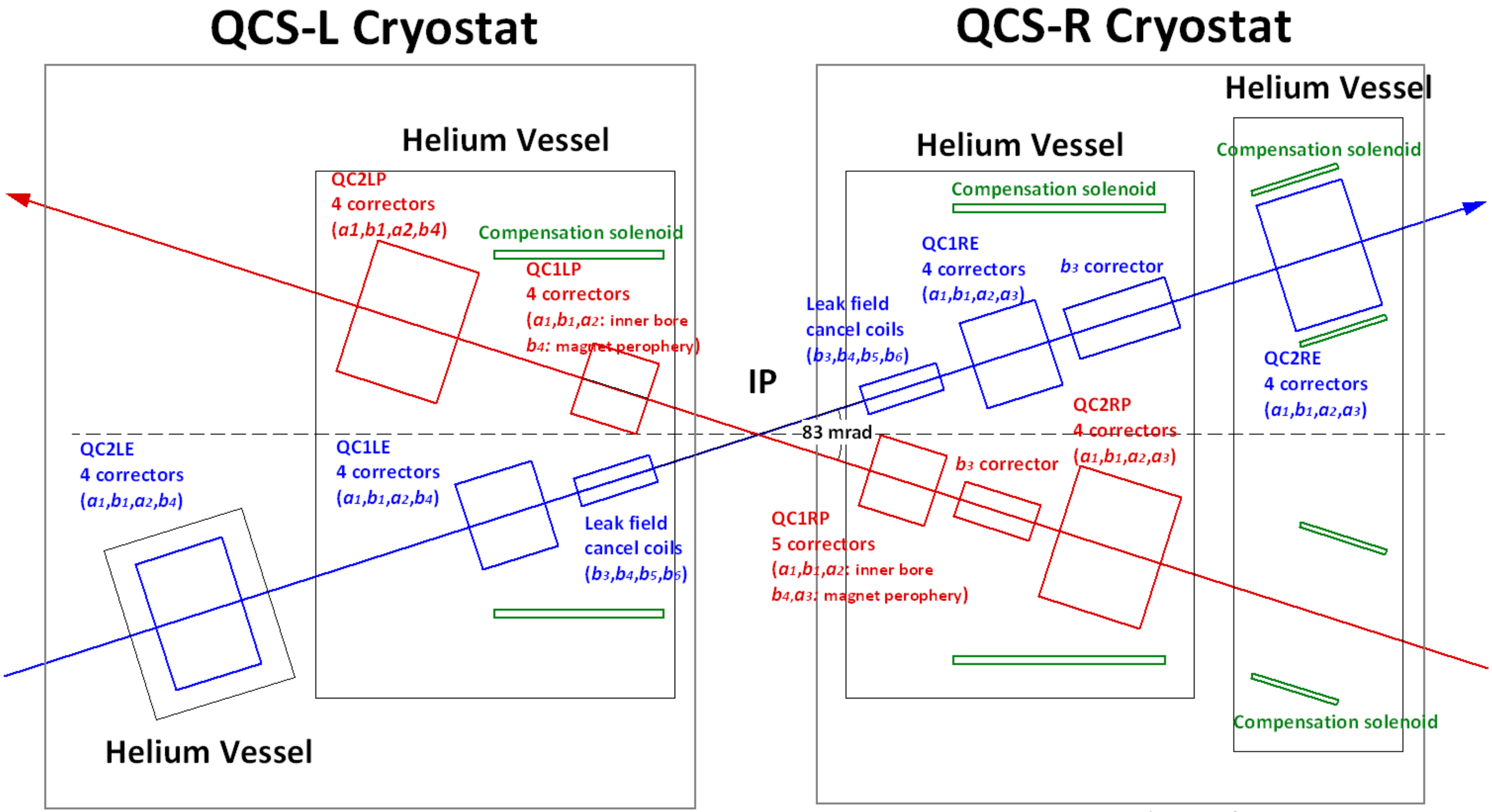
1. SC magnet system of the SuperKEKB IR
2. Main quadrupole magnets
3. Correctors and leak field cancel coils
4. Compensation solenoids
5. Assembly of magnet-cryostat
6. Summary

IR Magnets Overview



Belle-II particle detector

S.C. Magnet System



Target luminosity = 8 × 10^{35} cm^{-2} s^{-1}

Beam size at IP: e- = 62 nm, e+= 46nm

S.C. quadrupole: 8

S.C. solenoid: 4

S.C. corrector: 43

S.C. Magnets

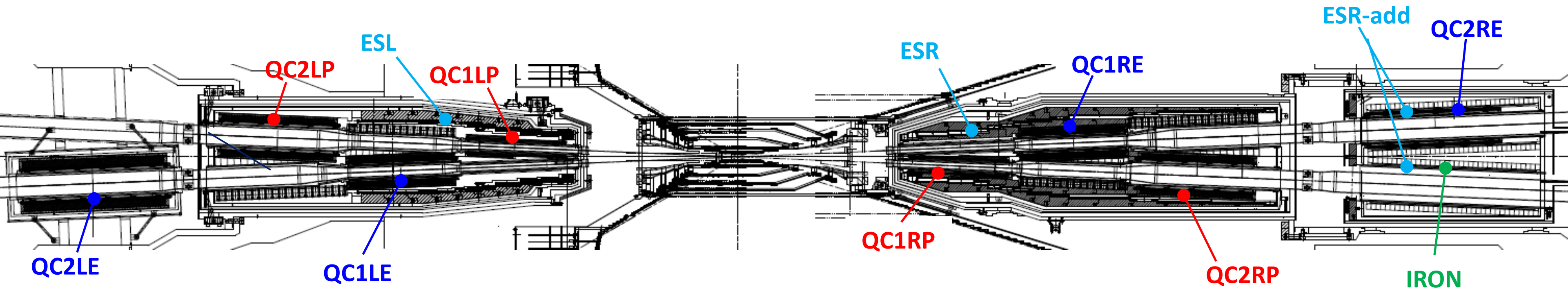
- **Main quadrupoles [QC1, QC2]**
  - Consisting final beam focusing system with quadrupole doublets.

- **Correctors [a_1, b_1, a_2, a_3, b_3, b_4]**
  - a_1, b_1, a_2: magnetic alignment of magnetic center and mid-plane of main quadruple.
  - a_3, b_3: correction of sextupoles induced by magnet construction errors.
  - b_4:increasing the dynamic transverse aperture (increasing the Touschek life time).

- **Compensation solenoid[ESR, ESL]**
  - Canceling the integral solenoid field by the particle detector (Belle II).
  - By tuning the B_z' profile, the beam vertical emittance can be minimized.
  - The compensation solenoids are designed to be overlaid on the quadrupoles and correctors.

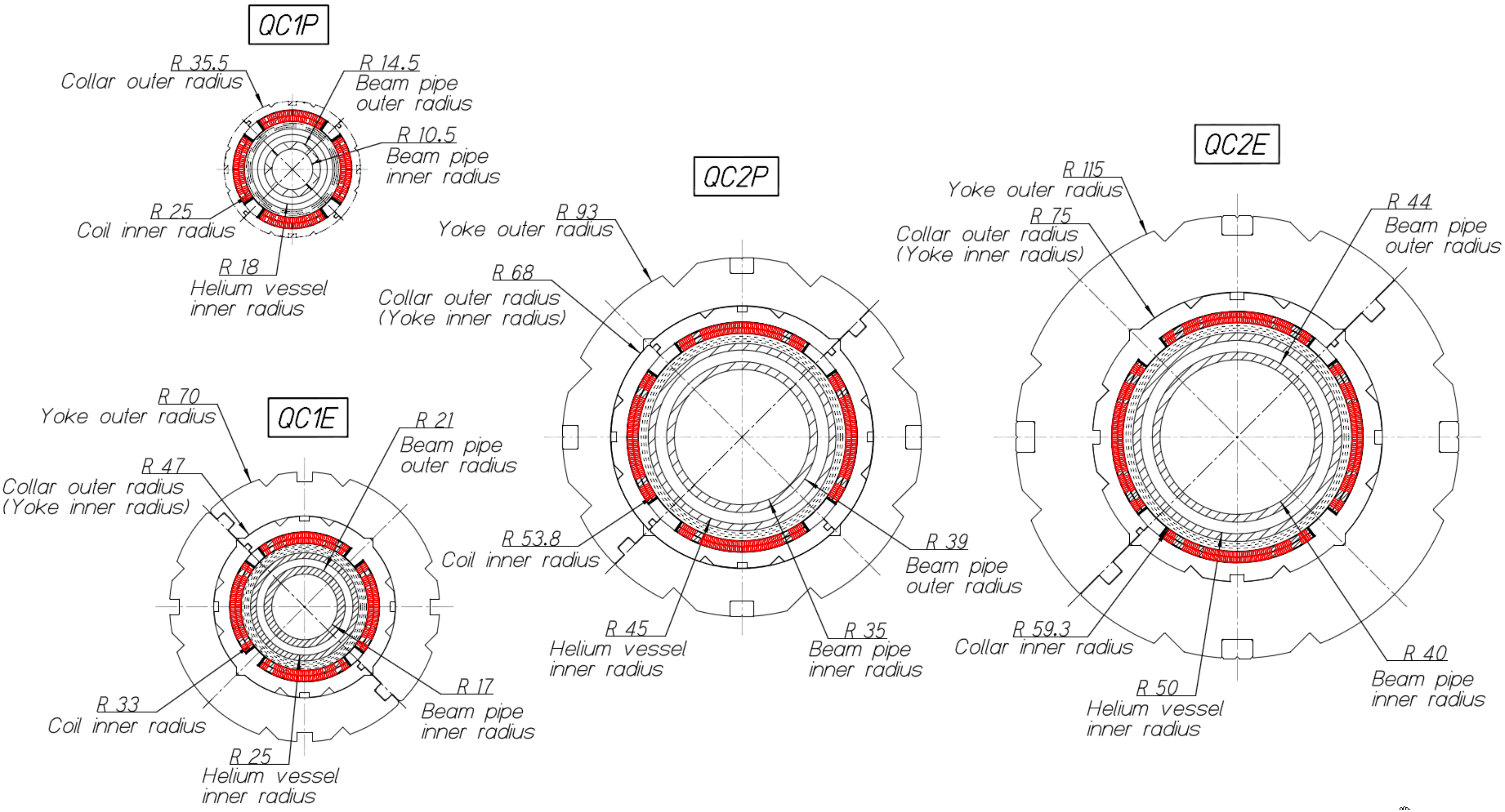
- **Leak field cancel coils [b_3, b_4 , b_5, b_6]**
  - Canceling the leak field on the electron beam line from QC1P (collared magnet).

S.C. magnets in SuperKEKB IR

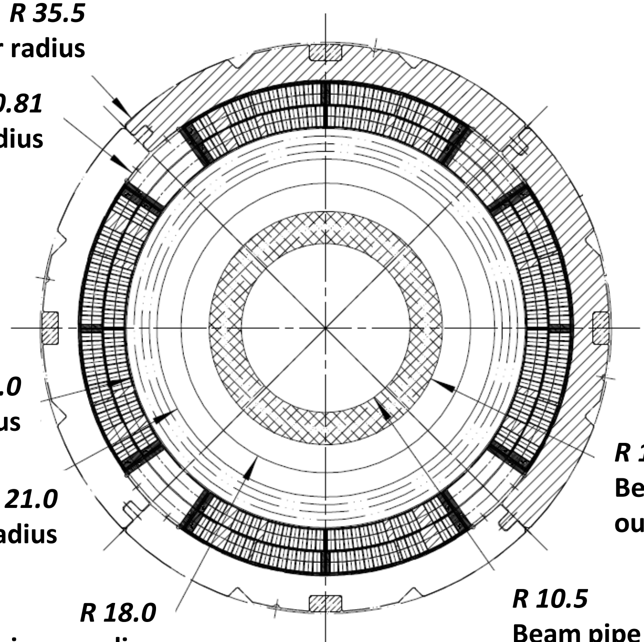


	Integral field gradient, (T/m)･m Solenoid field, T	Magnet type	Z pos. from IP, mm	θ, mrad	ΔX, mm	ΔY, mm
QC2RE	13.58 [32.41 T/m × 0.419m]	**Iron Yoke**	2925	**0**	**-0.7**	**0**
QC2RP	11.56 [26.28 × 0.410]	**Permendur Yoke**	1925	**-2.114**	**0**	**-1.0**
QC1RE	26.45 [70.89×0.373]	**Permendur Yoke**	1410	**0**	**-0.7**	**0**
QC1RP	22.98 [68.89×0.334]	**No Yoke**	935	**7.204**	**0**	**-1.0**
QC1LP	22.97 [68.94×0.334]	**No Yoke**	-935	**-13.65**	**0**	**-1.5**
QC1LE	26.94 [72.21×0.373]	**Permendur Yoke**	-1410	**0**	**+0.7**	**0**
QC2LP	11.50 [28.05 × 0.410]	**Permendur Yoke**	-1925	**-3.725**	**0**	**-1.5**
QC2LE	15.27 [28.44×0.537]	**Iron Yoke**	-2700	**0**	**+0.7**	**0**

Cross section of four quadrupoles



QC1P (No iron yoke)



QC1P magnet cross section

QC1P magnet design (QC1RP, QC1LP)

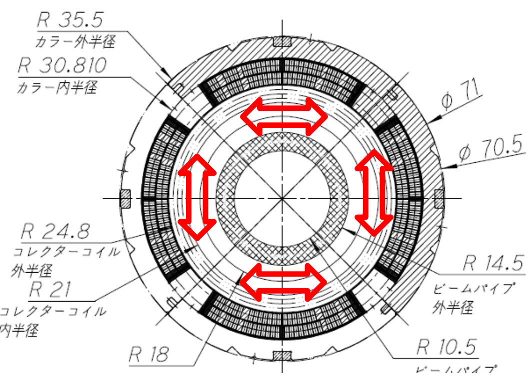
- Same design for QC1RP and QC1LP
- 2 layer coils [double pancake]
- **SC correctors [designed by BNL]**
  - **a_2, b_1 and a_1 inside of the magnet bore**
  - **b_4 , a_3 outside of the magnet collar**
- Cryostat inner bore radius=18.0 mm
- Beam pipe (warm tube)
  - inner radius=10.5 mm, outer radius=14.5 mm

Superconducting cable (NbTi)

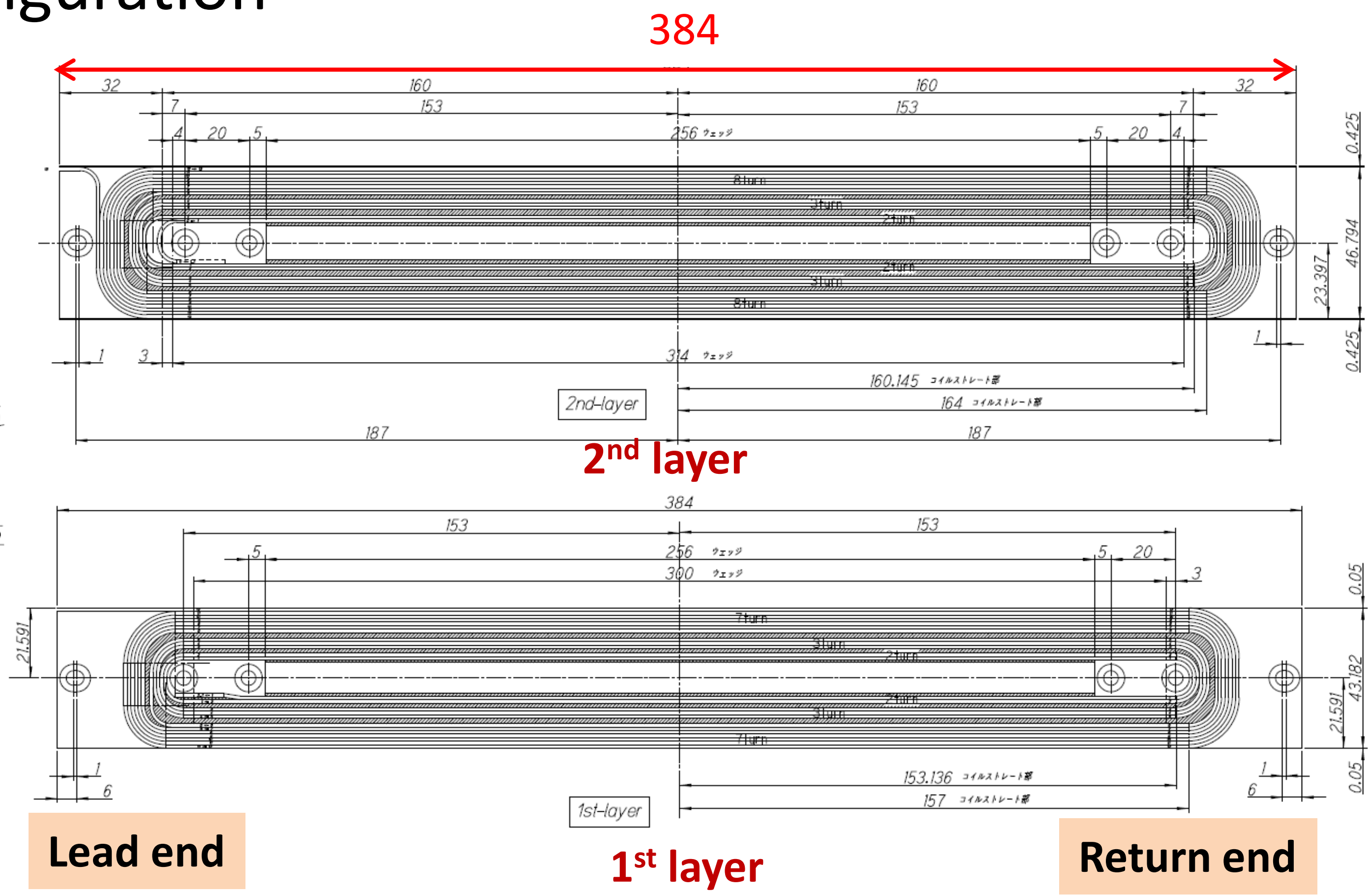
- Cable size : 2.5 mm × 0.93 mm
- **Keystone angle = 2.09 degree**
  - Each magnet has the optimized angle.
- Number of strands = 10
- Strand diameter = 0.5 mm
- Cu/SC ratio = 1.0
- Critical current (measured) = 3160 A @5 T & 4.2 K

3D magnet design of QC1R/LP

QC1P coil configuration

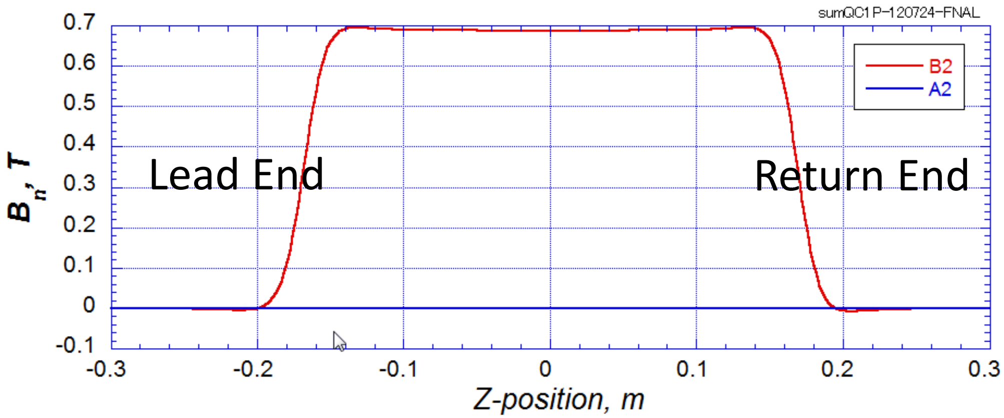


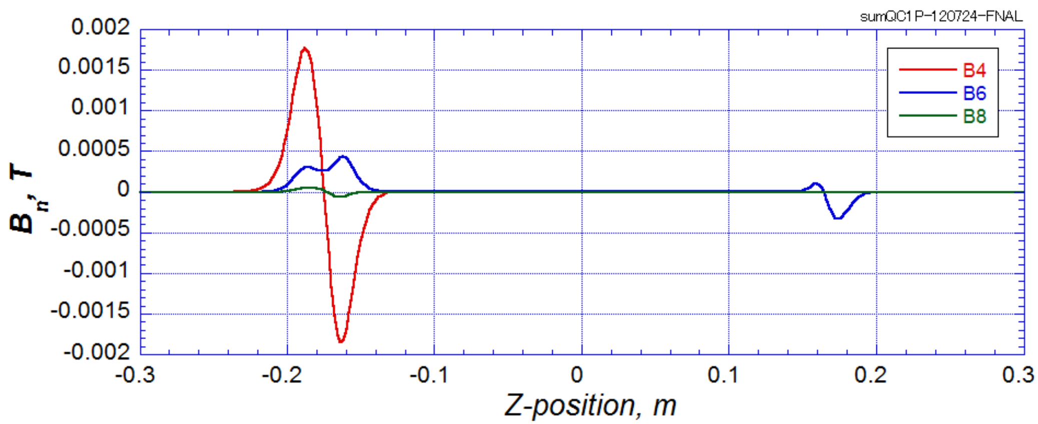
Mirror symmetry for reducing the skew quadrupole field in the lead end.

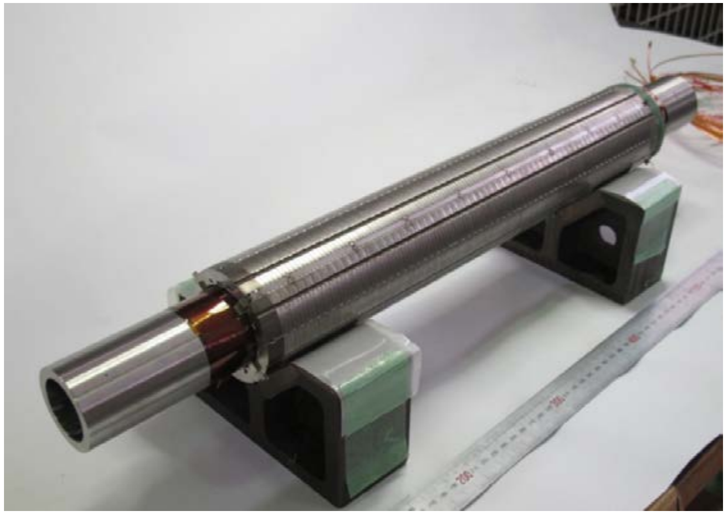


Field profile of QC1R/LP

IP-side





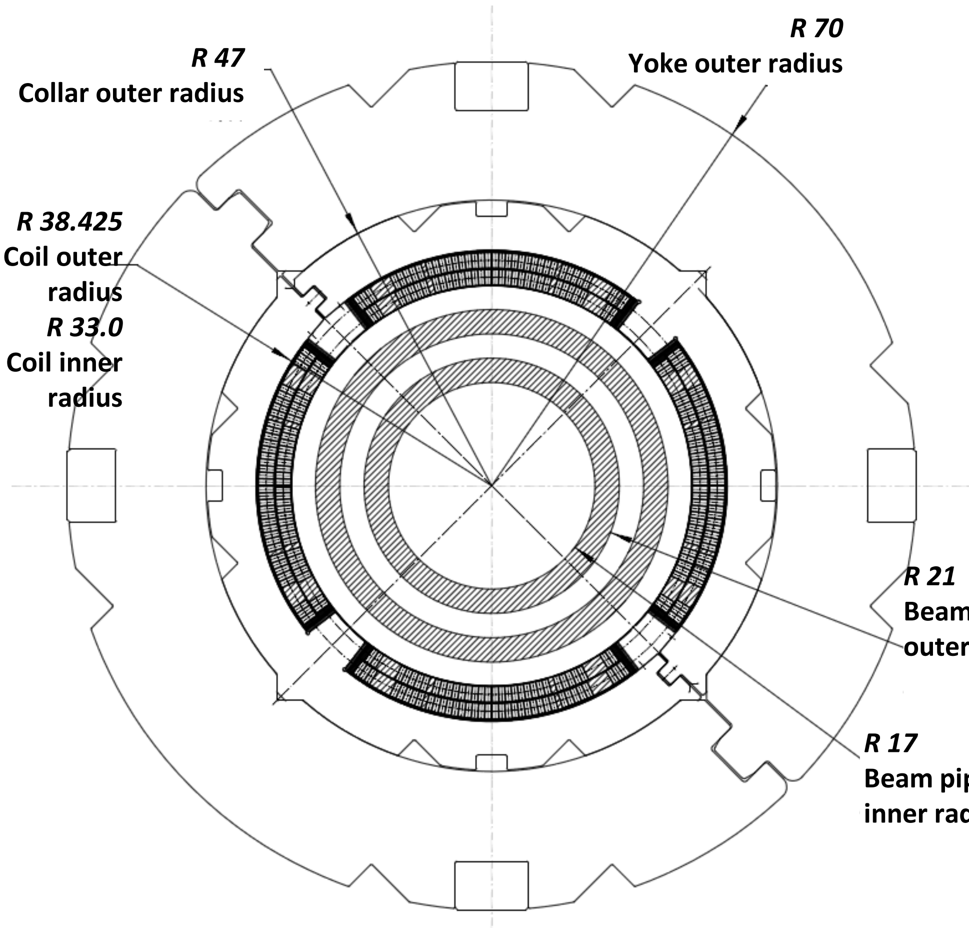


Multipole field at R=10 mm
Integral $b_4 = 2.38 \times 10^{-5}$
Int. $b_6 = 5.42 \times 10^{-5}$
Int. $b_8 = 1.10 \times 10^{-6}$

Peaks of $B_4 = \pm$ 18 Gauss at 1625 A
Peaks of B_6 = + 4.4/-3.3 Gauss at 1625 A

Lead end locates at IP side in the cryostat.

QC1E magnet design: Permendur yoke



QC1E magnet cross section

QC1E magnet design (QC1RE, QC1LE)

- Yoked magnet: **Permendur yoke**
- 2 layer coils [double pancake]
- $I_{op@4S}$=1577 A for QC1LE
  - G =72.2 T/m, L_{eff} = 0.373 m
- **SC correctors**
  - a_2, b_1, a_1 inside of the magnet bore
  - b_4 [QC1LE], a_3 [QC1RE] inside of the magnet bore
- Cryostat inner bore radius=25.0 mm
- Beam pipe (warm tube)

Proto-types of QC1 magnets

- QC1P and QC1E proto-type test results
  - The sextupole error field at the level of 10^{-3} to the quadrupole field was measured.
  - **Sextupole correctors were introduced into the magnet system in the right side.**

QC1P Proto-type Magnet

Measured G = 68.38 T/m at I=1626A
Design G = 68.84 T/m

Integral field components at R=9.54 mm

n	a_n	b_n
2	-0.000	10000
3	**2.82**	**3.66**
4	2.08	0.24
5	0.35	0.23
6	0.03	-0.59
7	0.07	0.13
8	0.03	0.01
9	-0.08	0.05
10	0.02	0.01

QC1E Proto-type Magnet

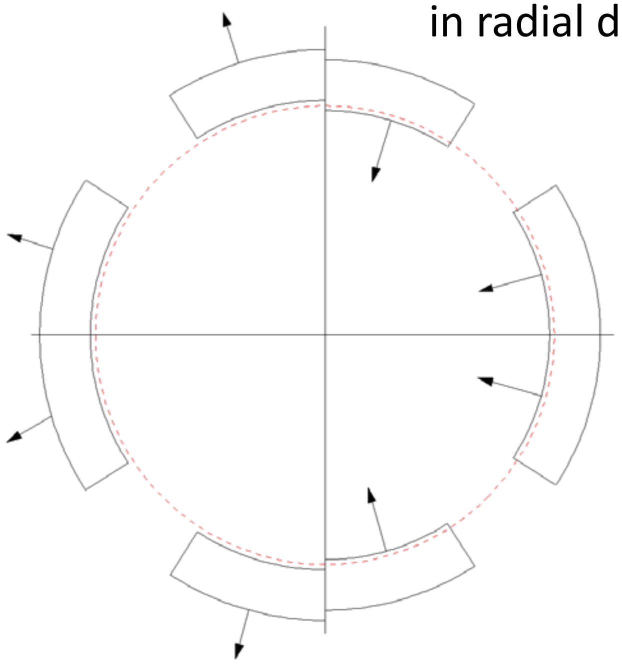
Measured G = 70.07 T/m at I=1560.6A
Design G = 70.63 T/m

Integral field components at R=15 mm

n	a_n	b_n
2	-0.000	10000
3	**1.78**	**8.59**
4	0.44	-0.68
5	0.23	-1.83
6	-0.39	-1.85
7	-0.09	0.10
8	0.69	-0.02
9	0.51	-0.09
10	-0.10	-0.62

a_3 and b_3 error field

- Sextupoles are produced by the dipole deformation of four coils



- Δ r = 50 μm
  - $b_3 = 13.62 \times 10^{-4}$
  - $a_3 = 0$
  - $b_4 = 0$
  - $a_4 = 0$
  - $b_5 = -1.63 \times 10^{-4}$
  - $a_5 = 0$
- Δ r = 20 μm
  - $b_3 = 5.45 \times 10^{-4}$
  - $a_3 = 0$
  - $b_4 = 0$
  - $a_4 = 0$
  - $b_5 = -0.65 \times 10^{-4}$
  - $a_5 = 0$

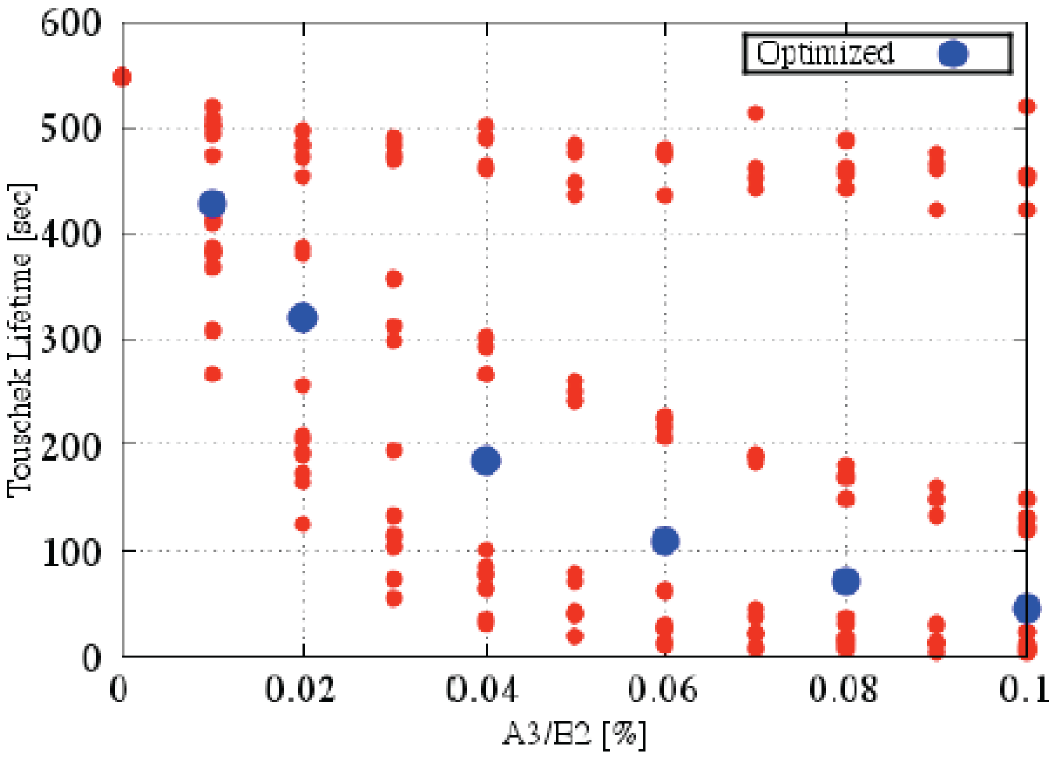
$b_3 = 8.6 \times 10^{-4}$ corresponds to Δr = 32 μm.

The geometry error of 32 μm is comparable to the machining accuracy of the magnet components. The a_3 and b_3 correctors are designed to be 0.1 % of the b_2 field.

Effect of a_3 on beam life time

Skew Sextupole Error Field

- Analogous calculation for skew sextupole error field.
- Different feature compared to the normal sextupole case.
- DA Improvement is not enough level.



Integral field quality of the real magnets
(measured under solenoid fields)

	QC1LP at R=10mm, I=1.71 kA		QC1RP at R=10mm, I=1.71kA		QC2LP at R=30mm, I=0.91kA		QC2RP at R=30mm, I=0.91kA	
n	a_n	b_n	a_n	b_n	a_n	b_n	a_n	b_n
1	790.2	232.9	1265.4	-140.25	399.7	13.8	-70.01	40.84
2	0.	10000.	0.	10000.	0.	-10000.	0.	-10000.
3	**-0.07**	**1.69**	**0.65**	**-0.91**	**-1.03**	**2.61**	**2.58**	**-0.09**
4	0.52	0.01	-0.94	-0.66	0.20	-0.20	-1.48	-0.22
5	0.01	-0.38	-0.35	0.35	0.92	0.32	-0.21	-0.07
6	-0.28	-0.10	0.37	-0.06	0.31	-3.58	0.62	-4.69
7	0.04	0.05	0.01	-0.06	-0.04	0.04	-0.21	0.00
8	0.07	-0.03	-0.04	-0.04	0.07	0.03	-0.07	0.07
9	0.10	-0.06	-0.01	0.05	-0.48	0.03	-0.12	-0.20
10	-0.03	-0.18	0.04	-0.18	0.21	0.86	0.34	1.77

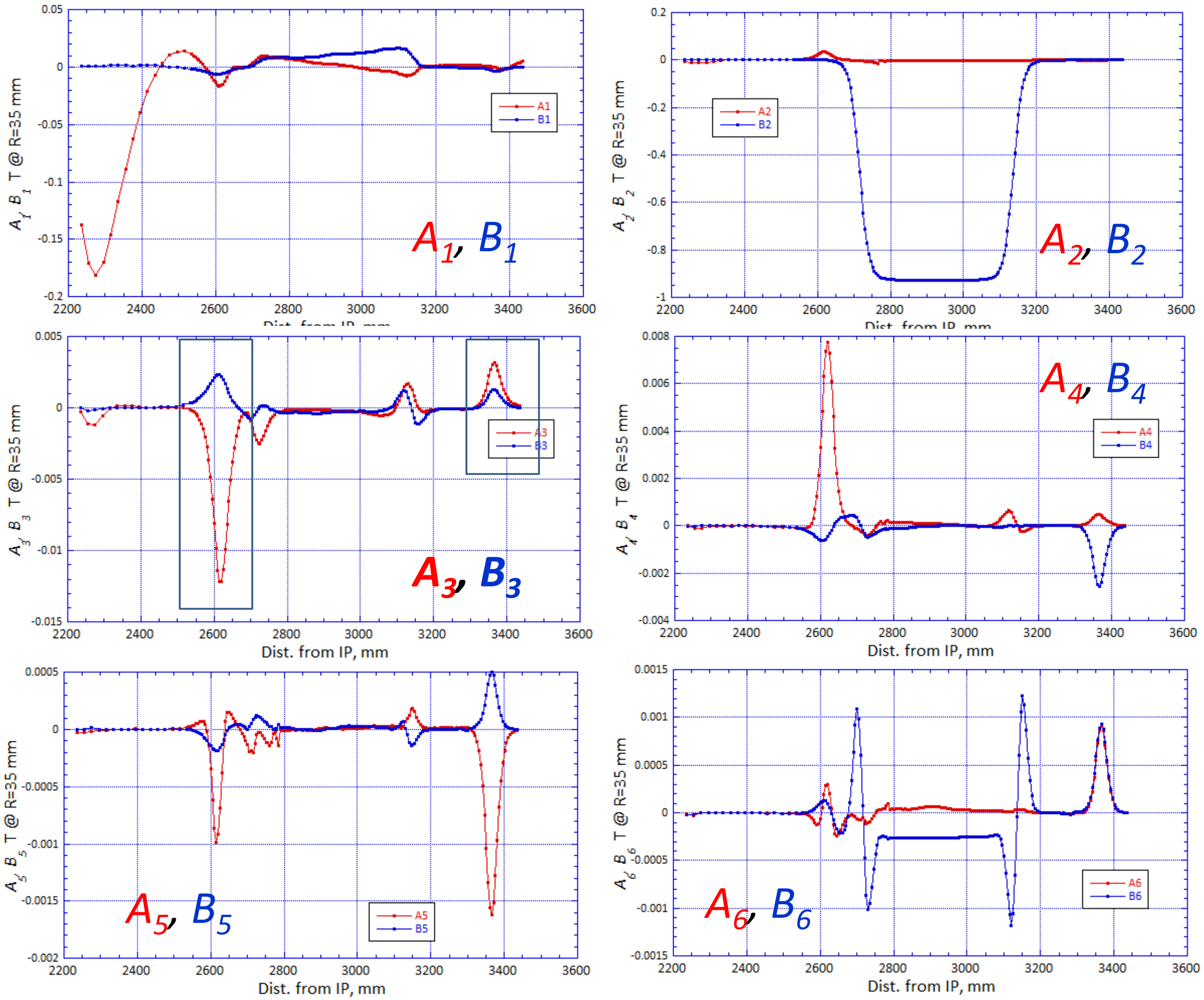
Integral field quality of the real magnets
(measured under solenoid fields)

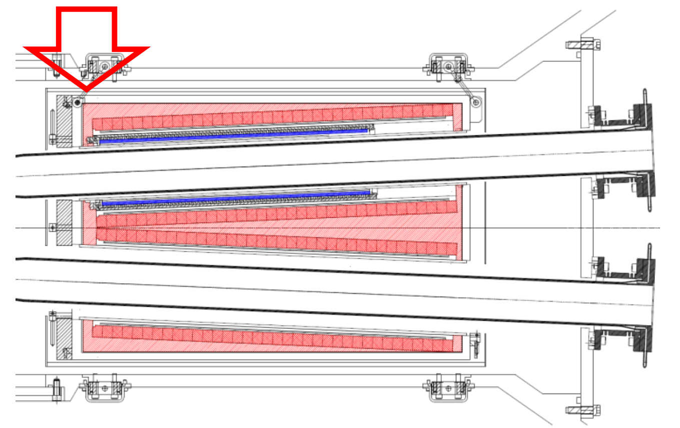
	QC1LE at R=15mm, I=1.71kA		QC1RE at R=15mm, I=1.71kA		QC2LE at R=35mm, I=1.11kA		QC2RE at R=35mm, I=1.11kA	
n	a_n	b_n	a_n	b_n	a_n	b_n	a_n	b_n
1	191.7	-313.2	131.2	-145.4	-12.8	170.64	15.4 (38.9)	114.0 (106.5)
2	0.	10000.	0.	10000.	0.	-10000.	0.	-10000.
3	**-0.59**	**0.72**	**0.97**	**-0.47**	**-1.44**	**-1.25**	**-18.9 (-4.79)**	**2.84 (-2.90)**
4	0.21	-0.24	-0.05	-0.18	-1.88	-0.29	8.09 (0.60)	-0.66 (0.04)
5	-0.20	-0.28	0.02	0.03	-0.63	0.16	-0.42 (0.40)	-0.21 (-0.10)
6	0.01	1.04	-0.07	0.92	0.18	-4.66	-0.22 (-0.19)	-1.60 (-1.95)
7	0.02	0.05	0.10	-0.02	-0.01	0.02	-0.11 (-0.05)	0.20 (0.14)
8	-0.09	-0.10	0.02	-0.01	-0.22	0.06	-0.06 (0.05)	0.16 (0.11)
9	-0.22	0.57	0.08	0.17	-0.20	-0.17	0.02 (-0.03)	-0.25 (-0.17)
10	-0.09	-0.08	-0.02	-0.60	0.08	2.22	0.06 (0.05)	1.80 (1.80)

Without excitation of solenoids

QC2RE field profile along the beam line

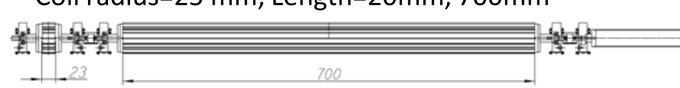
(measured under solenoid fields)





For QC1P and QC1E:
Coil radius=12.5 mm, Length=20mm, 600mm

For QC2P:
Coil radius=25 mm, Length=20mm, 700mm

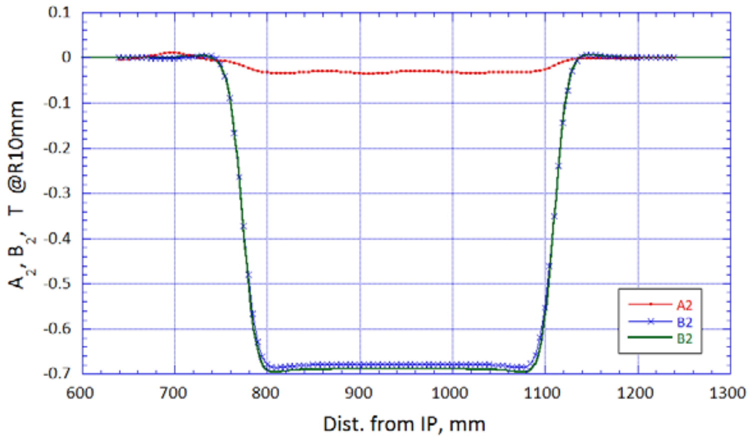


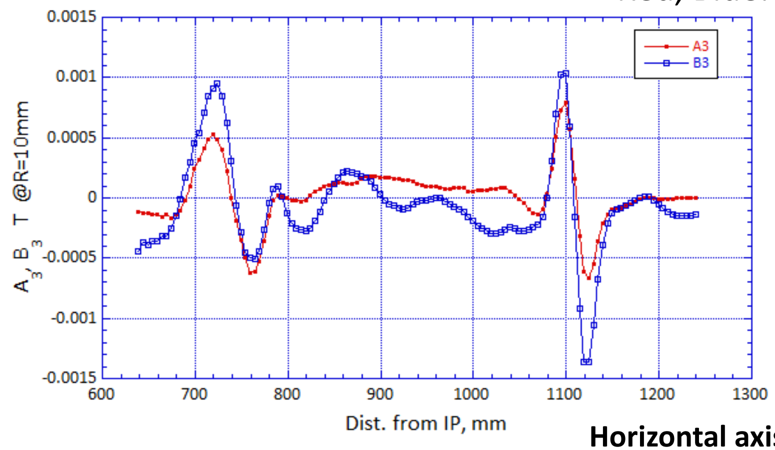
For QC2E:
Coil radius=33 mm, Length=20mm, 800mm

QC1LP field profile along the beam line
(measured under solenoid fields)

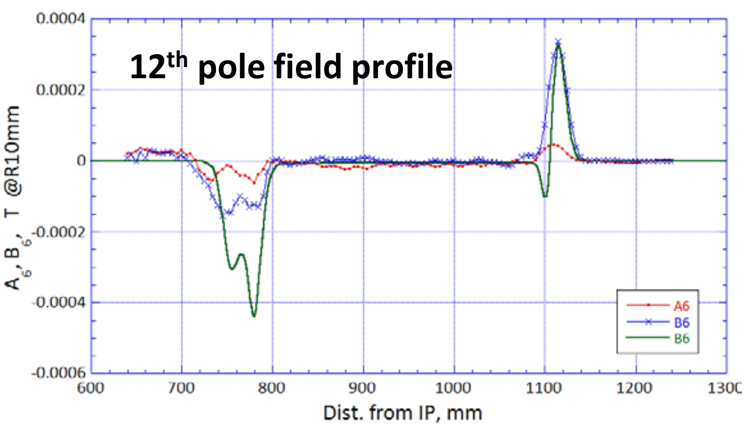
- Field profile of QC1LP along the beam line

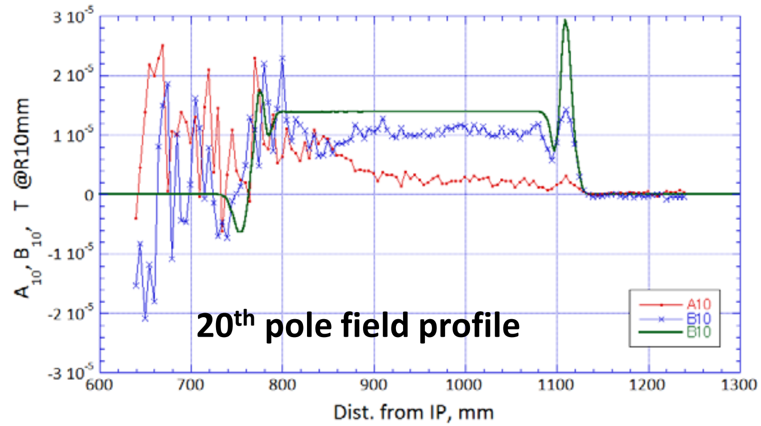
Green line: design
Red, Blue: measurement





Horizontal axis：distance from IP





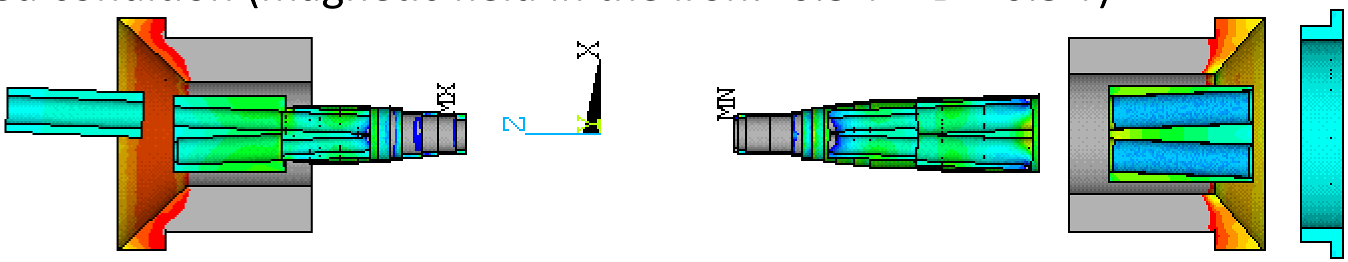
With the field profiles, the distances of the main quadrupole magnet centers from IP are calculated.
The field profiles will be built in the optics calculation model, and the influence on the beam operation will be studied.

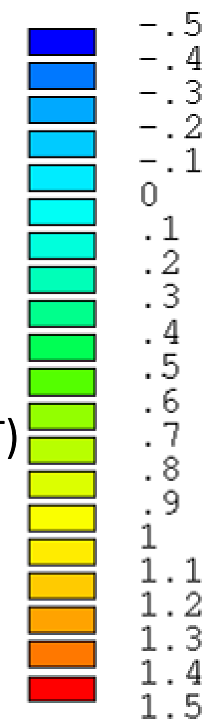
Magnet design: Permendur yoke

- The final focus system is designed to be operated under the Belle II solenoid field at 1.5 T.
- This field is cancelled with the accelerator compensation solenoids along the beam line. This cancellation is not perfect.

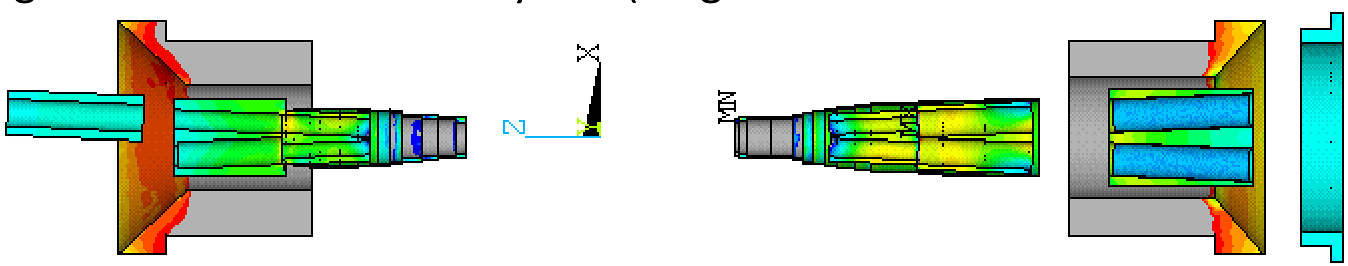
Field profile in the iron components (3D ANSYS)

Optimized condition (magnetic field in the iron: -0.5 T < B < 0.5 T)





Increasing Belle solenoid current by 1 % (magnetic field in the iron: -0.5 T < B < 1 T)



At the good cancelling condition, the insides of iron components have magnetic field at 0.5T .

Magnet design: Permendur yoke

- **Choice of Permendur for QC1E and QC2P Yoke.**
  1. Space between LER and HER beam lines along the QC1E is insufficient not to have leak field of QC1E in the LER beam area.
  2. Compensation of Belle solenoid field by the accelerator solenoid is not perfect in the local position.
     - The remanent solenoid field easily goes into the Yokes and the magnetic field in the yokes is enhanced.
  3. 12 GeV accelerator operation is the severer magnetic condition for the magnets than 4S (nominal) operation.

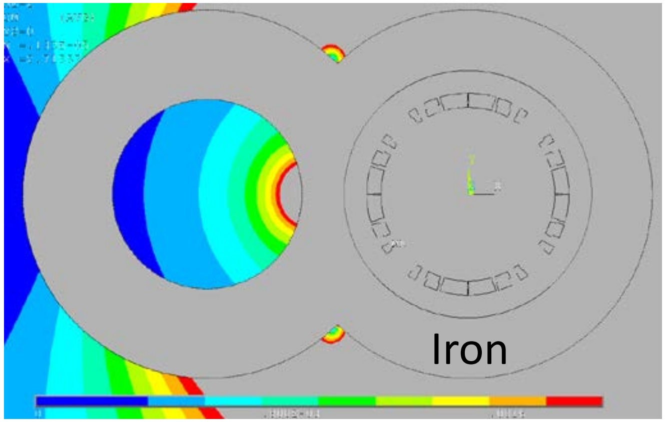
⇓

Permendur Yoke and Magnetic Shield

Magnet design: Permendur yoke

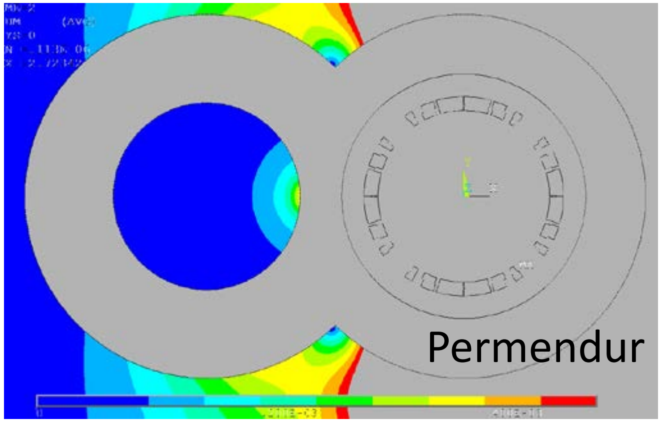
Comparison between Iron and Permendur

With 0.5 T field in the Yoke (4s)



0 Gauss 20 Gauss

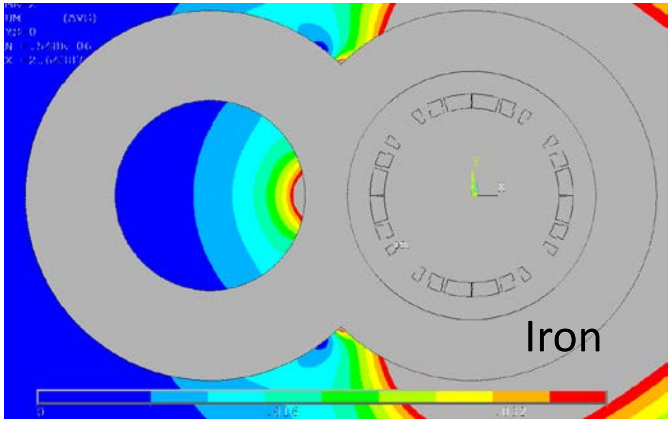
Leak field at e+ center = 6 Gauss



0 Gauss 5 Gauss

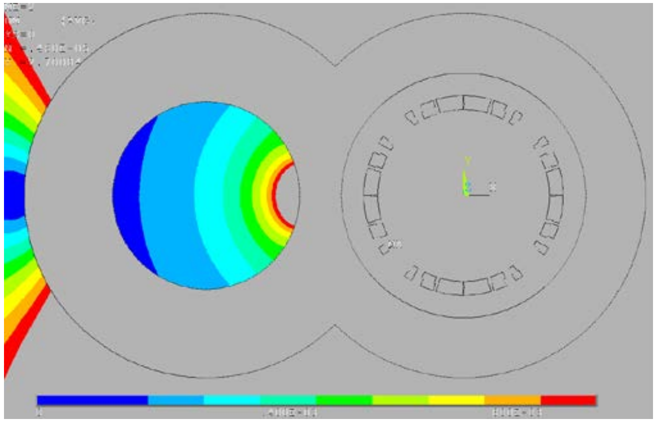
Leak field at e+ center <1 Gauss

With 1 T field in the Yoke (4s)



0 Gauss 400 Gauss

Leak field at the e+ center = 100 Gauss



0 Gauss 10 Gauss

Leak field at e+ center = 6 Gauss

SC correctors

Magnet	R_0 mm	I_{max} A	A_1 T·m	B_1 T·m	A_2 T	A_3 T/m	B_3 T/m	B_4 T/m^2
QC1LP	10	70	0.016 (0.69 mm)	0.016 (0.66 mm)	0.64 (13.9 mrad)			60
QC2LP	30	70	0.03 (2.61 mm)	0.03 (2.61 mm)	0.31 (13.5 mrad)			60
QC1LE	15	70	0.027 (1.43 mm)	0.046 (2.42 mm)	0.75 (15.9 mrad)			60
QC2LE	35	70	0.015 (1.6 mm)	0.015 (1.6 mm)	0.37 (16.7 mrad)			60

Magnet	R_0 mm	I_{max} A	A_1 T·m	B_1 T·m	A_2 T	A_3 T/m	B_3 T/m	B_4 T/m^2
QC1RP	10	60	0.016 (0.69 mm)	0.016 (0.66 mm)	0.64 (13.9 mrad)	16	16	60
QC2RP	30	60	0.03 (2.61 mm)	0.03 (2.61 mm)	0.31 (13.5 mrad)	1.6		
QC1RE	15	60	0.027 (1.43 mm)	0.046 (2.42 mm)	0.75 (15.9 mrad)	38		
QC2RE	35	60	0.015 (1.6 mm)	0.015 (1.6 mm)	0.37 (16.7 mrad)	8.1		
B.T. QC1RP and QC2RP	15	60					7.5	
B.T. QC1RE and QC2RE	30	60					4.8	

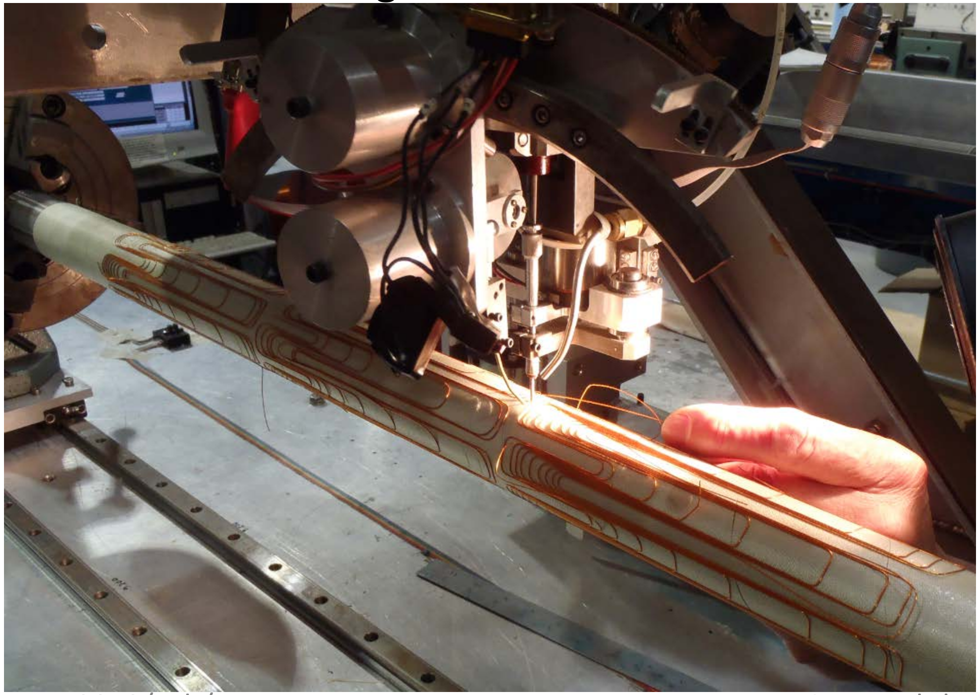
The number of correctors is 35, and they are wound in multi-layer for each main quadrupole.
The correctors are operated under the bias fields of solenoids and the quadrupole magnets.

- **The figures in parentheses are the correctable errors of magnetic axes and quadrupole angles, and parts of these fields are used in the optics design.**

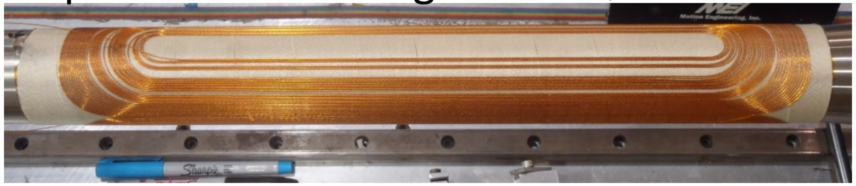
SC correctors

- SC correctors were constructed by BNL under the US-Japan research collaboration program.
- The spaces for the correctors were very tight, and then the coils were wound by the direct winding method.
  - Diameter of the S.C. conductor = ϕ0.35 mm, Critical current = 154 A at 4 T and 4.2 K
  - Multi-layered coils : Maximum layer number = 4 (from the space constraint between the bore of the main quadrupole magnet and the inner helium pipe.

BNL direct winding machine



Dipole corrector magnet for QC1LE

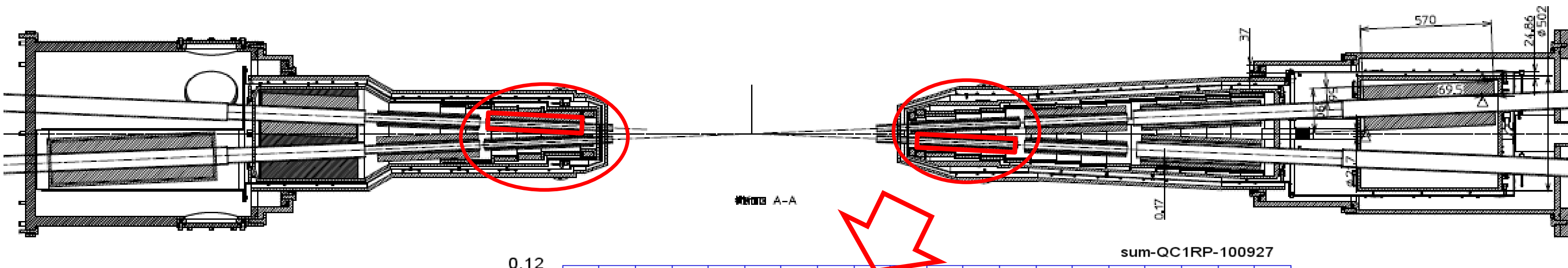


Sextupole QC1P leak field cancel magnet

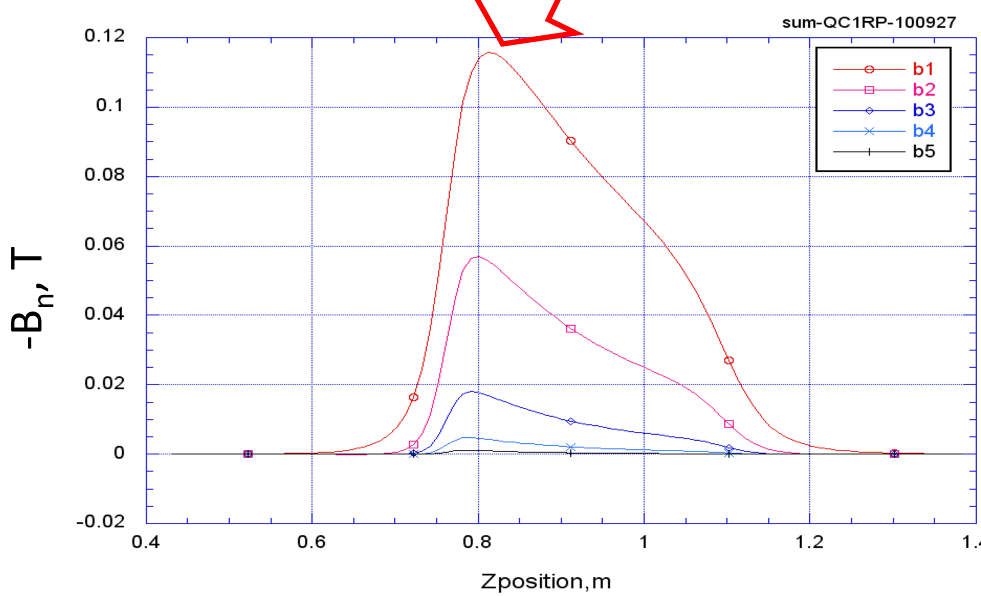
S.C. coil for QC1E magnet

SC leak field cancel coils

- QC1P for the e+ beam line is non-iron magnet and the e- beam line is very close to QC1P. The leak fields along the e- beam line by QC1P are calculated.
- ***B_3, B_4, B_5*** and ***B_6*** components of the leak fields are designed to be canceled with the SC cancel coils.
- B_1 and B_2 components are not canceled, and they are included in the optics calculation.
  - B_2 component is used for focusing and defocusing the e- beam.

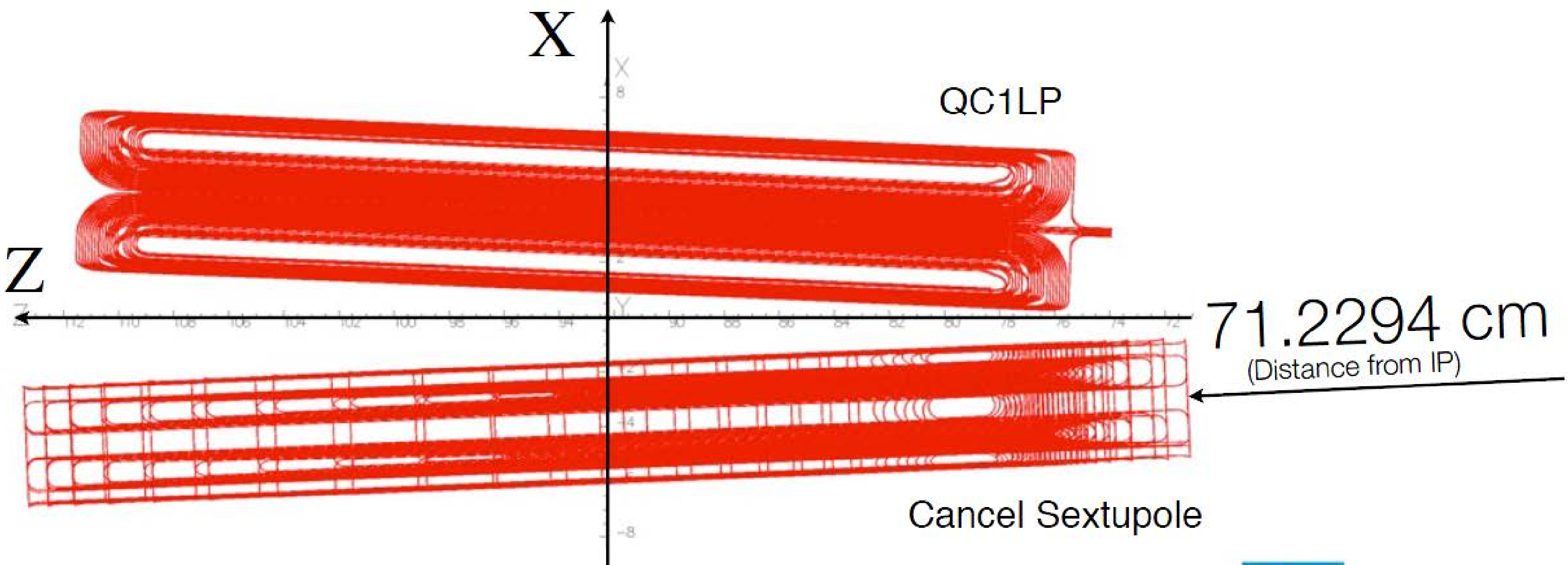


QC1RP leak field profile along the e- beam line



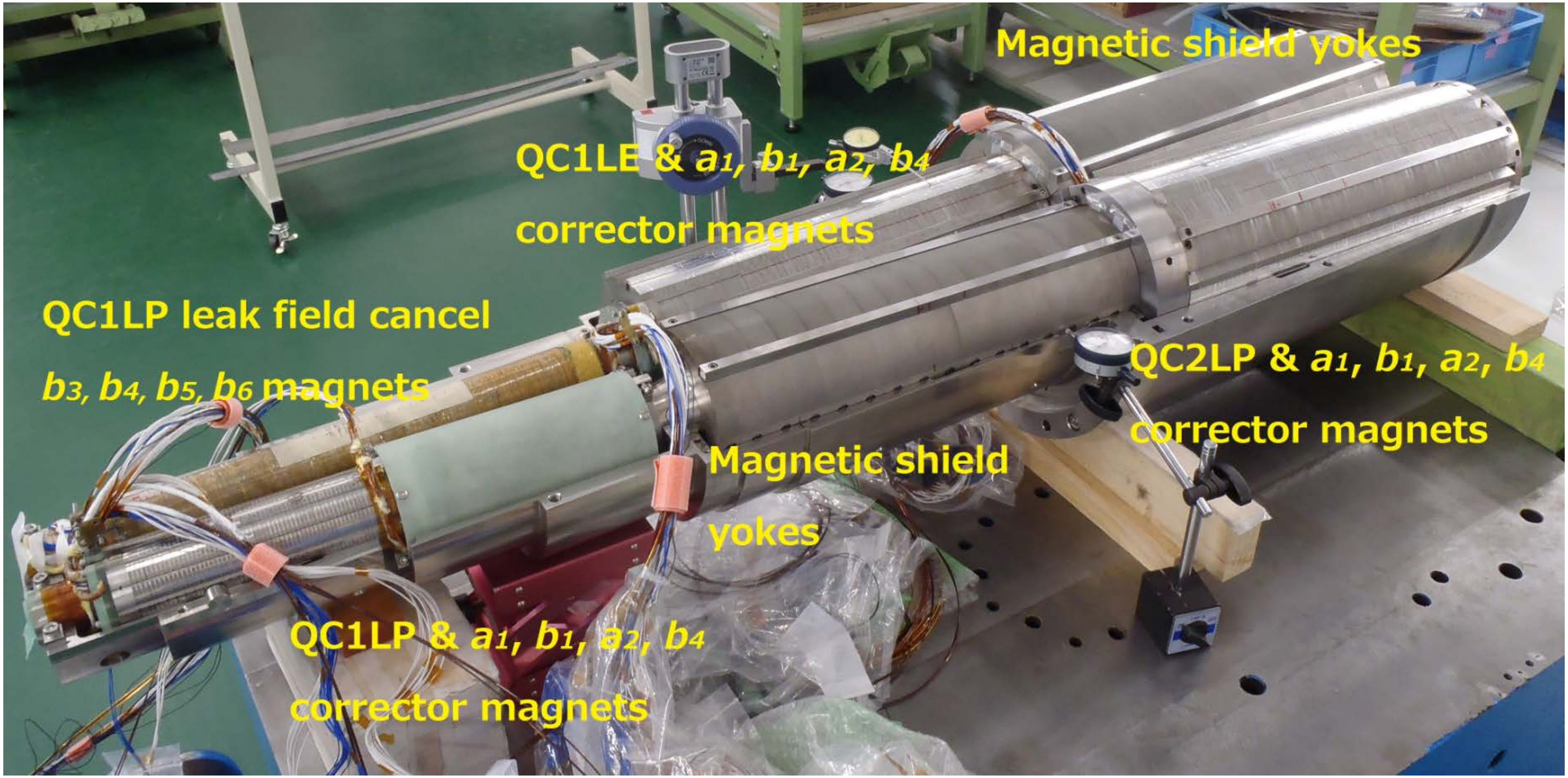
SC leak field cancel coils

- The leak field cancel coils were designed and constructed by BNL under the US-Japan research collaboration program.
- The field models were constructed with the collaboration between BNL and KEK.

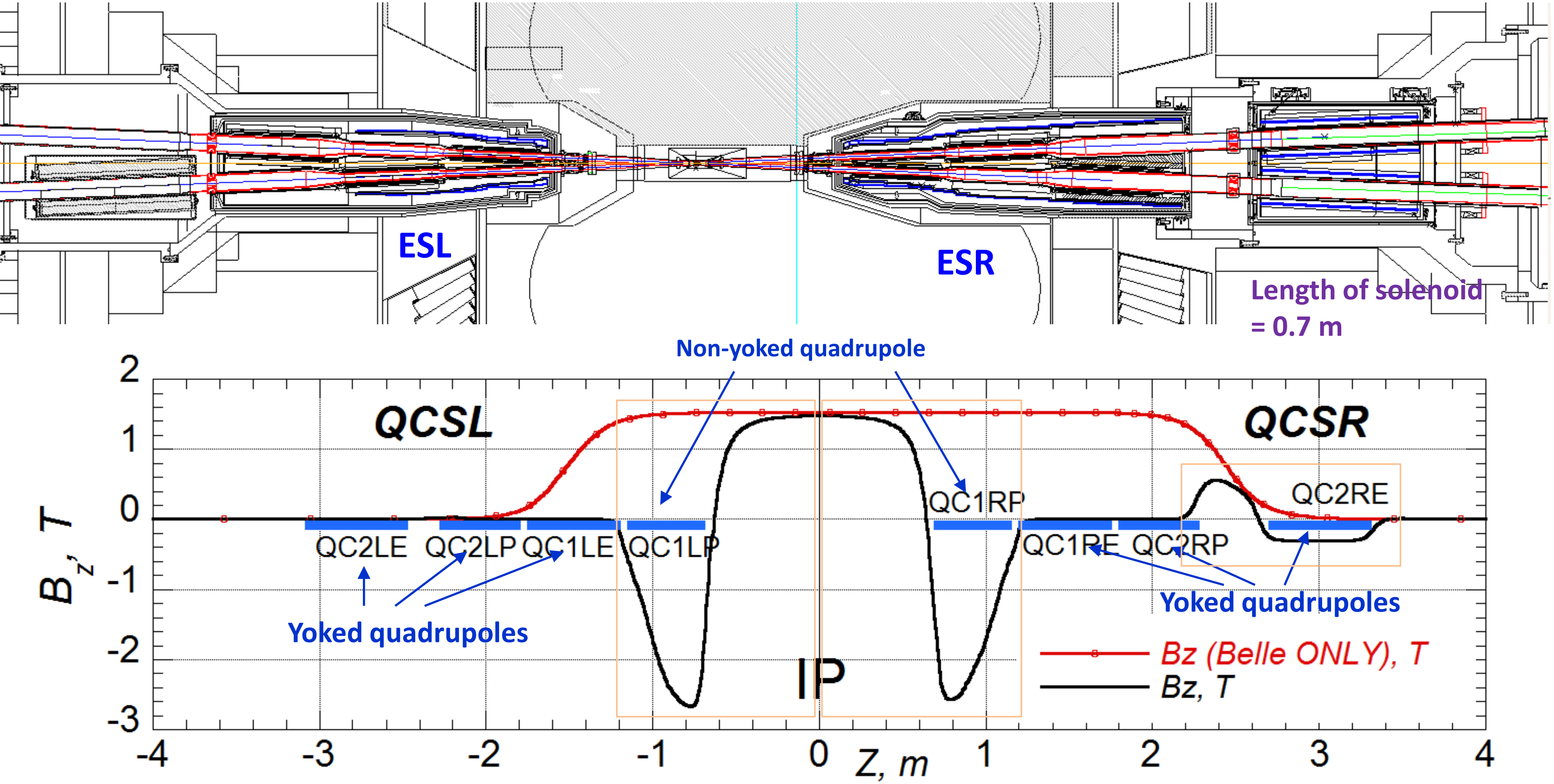


Cancel coil designed by B. Parker [BNL]
Sextupole cancel coil : 2 layer serpentine coils

Quadrupole magnets assembly

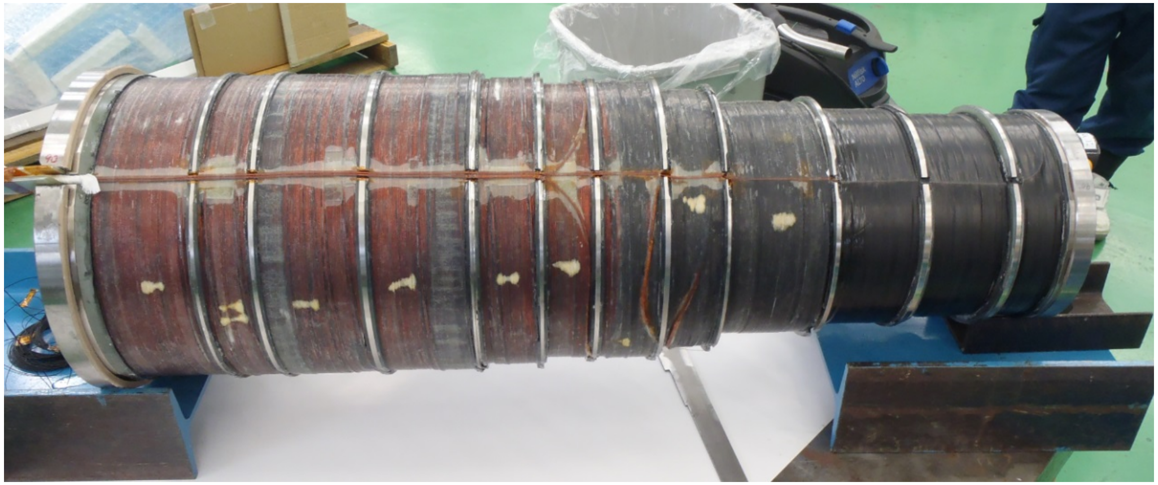


Compensation Solenoids



- In the left cryostat, one solenoid (12 small solenoids) is overlaid on QC1LP and QC1LE.
- In the right cryostat, the 1st solenoid (15 small solenoids) is overlaid on QC1RP, QC1RE and QC2RP.
  - The 2nd and 3rd solenoids on the each beam line in the QC2RE vessel.

Compensation Solenoids



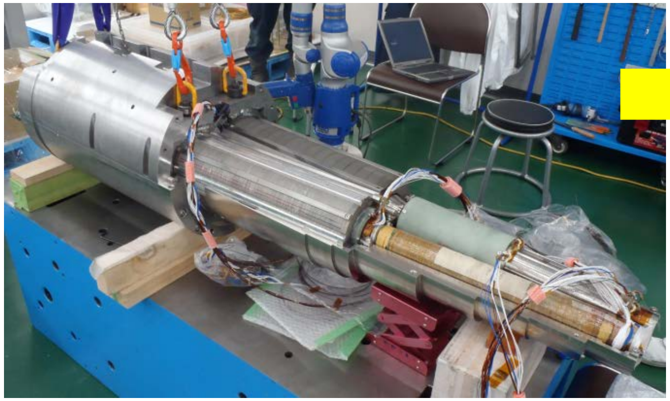
ESL:

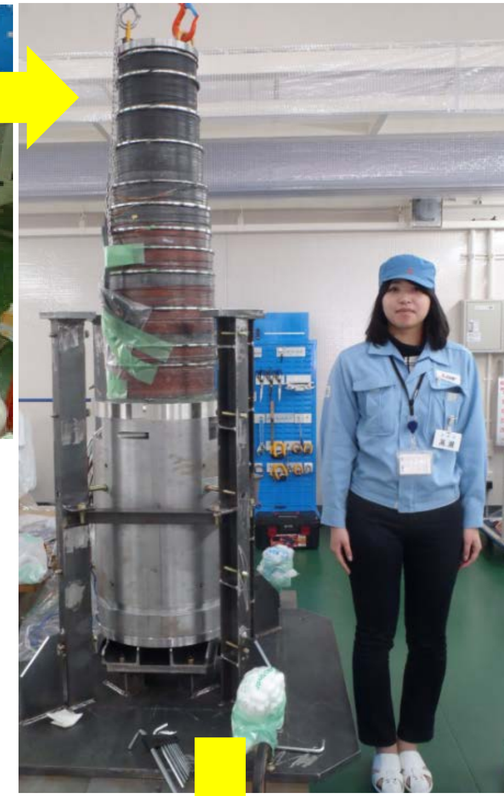
Magnet length= 914 mm
Maximum field at 403 A= 3.53 T
Stored Energy= 118 kJ

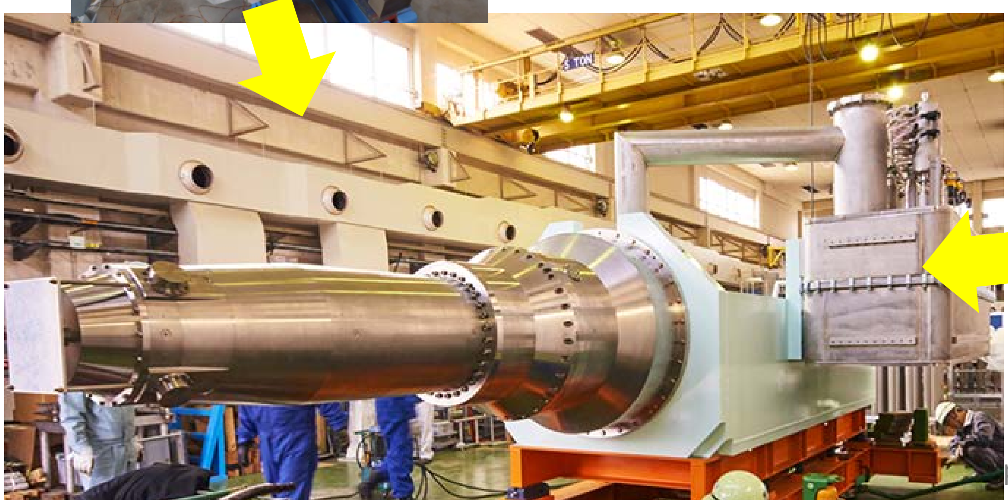
ESR1:

Magnet length= 1575 mm
Maximum field at 450 A=3.19 T
Stored Energy= 244 kJ
Cold diode quench protection system

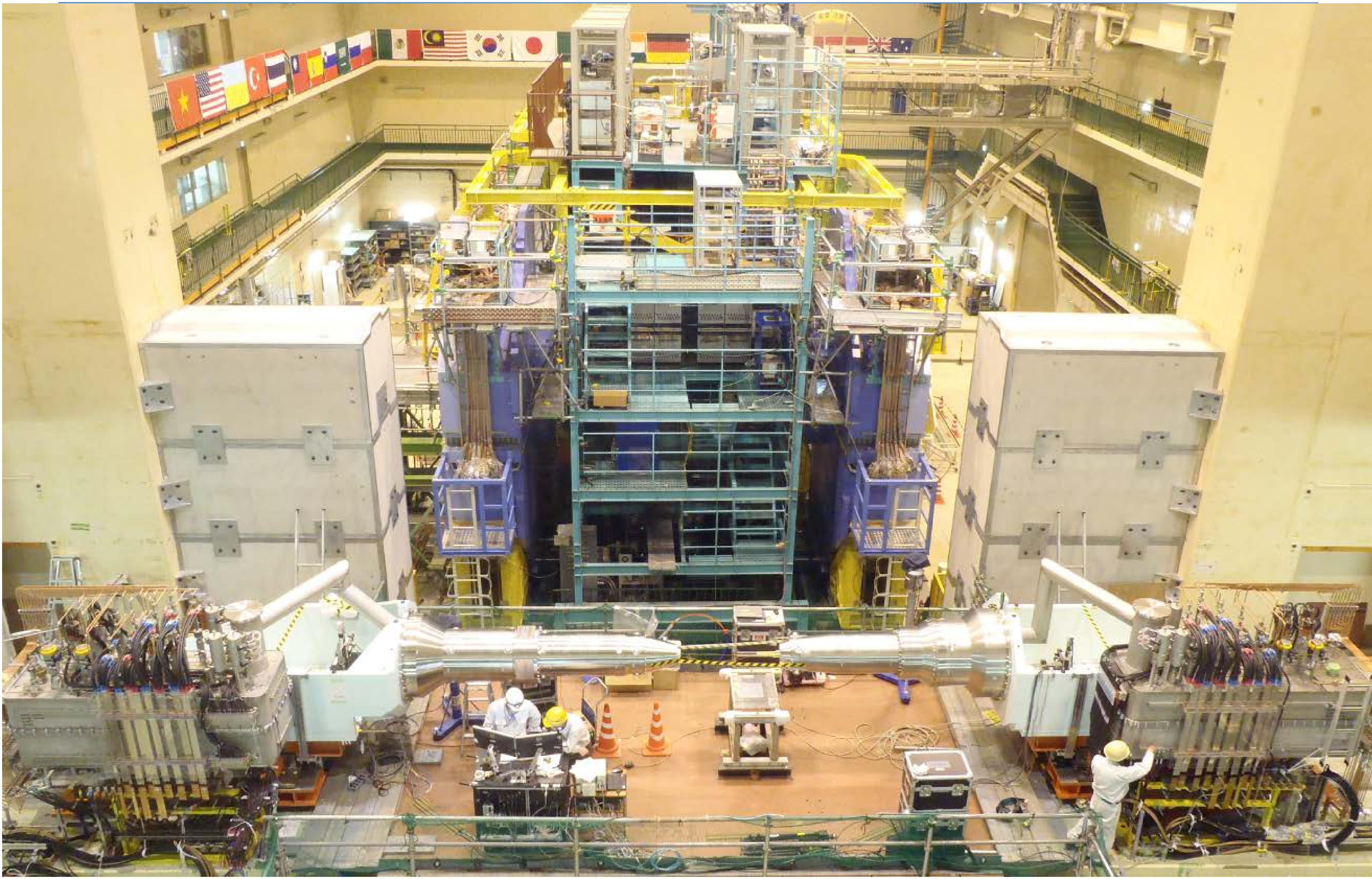
Assembly of magnet-cryostats



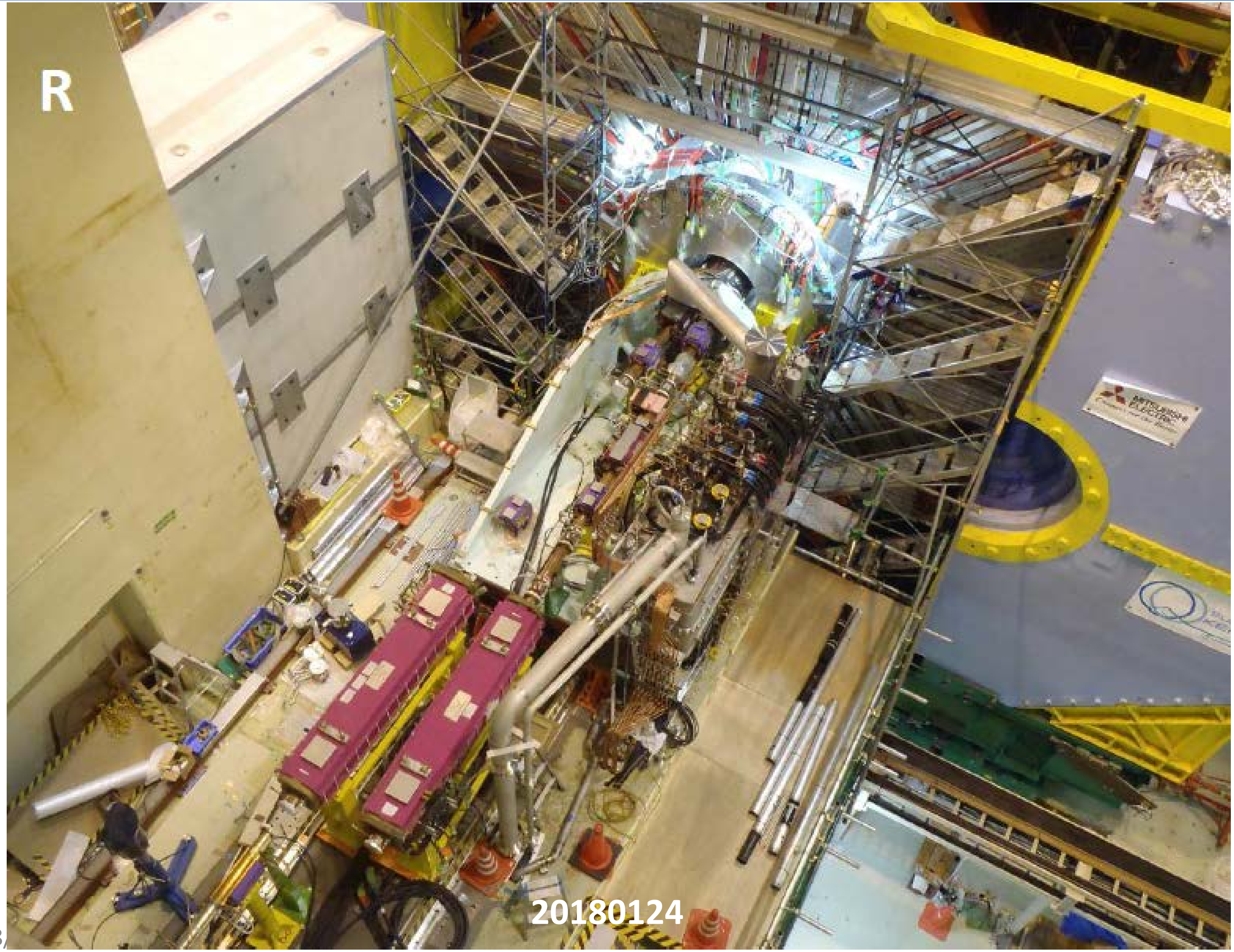




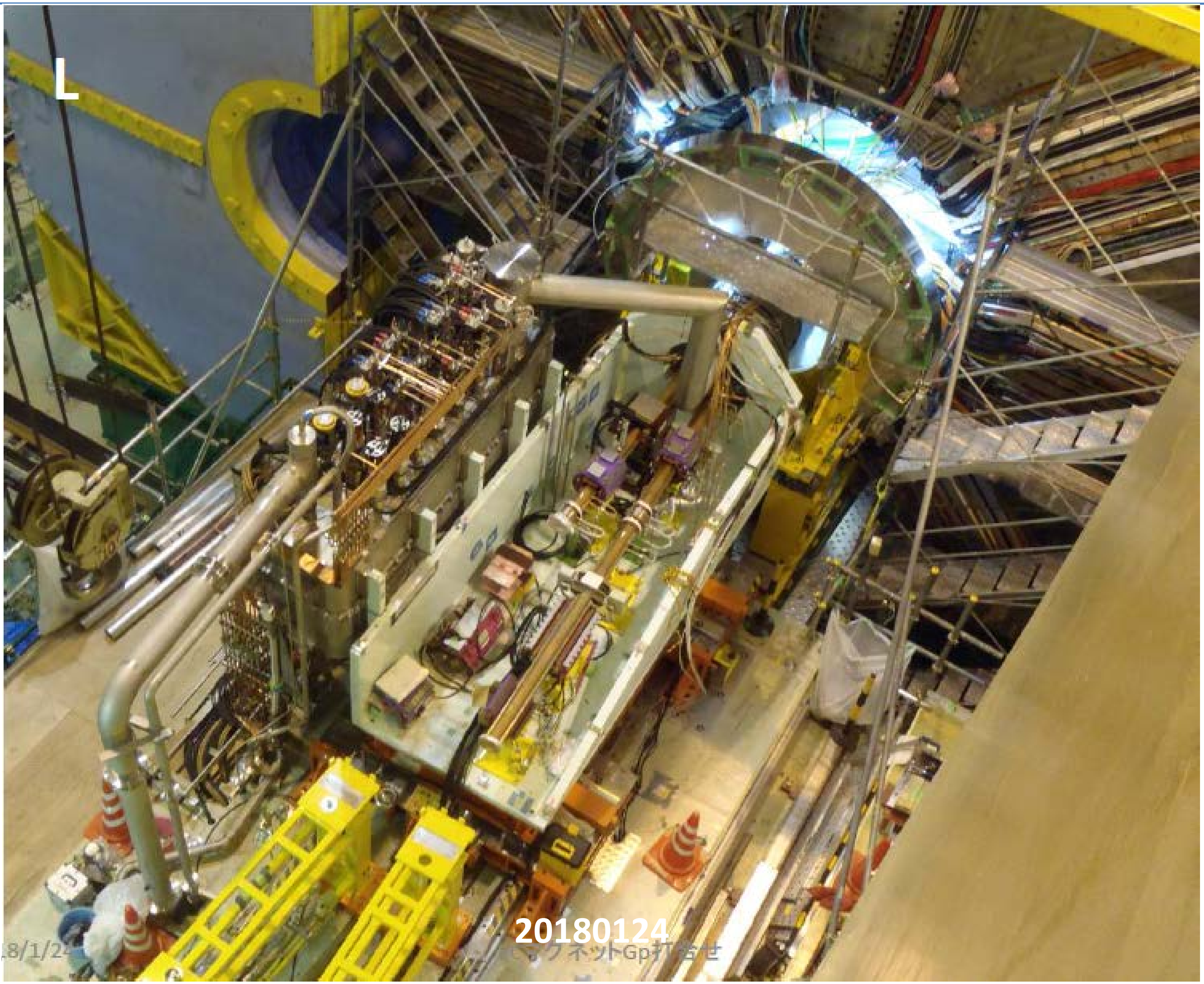
Magnet-cryostats in SuperKEKB-IR



Magnet-cryostats in SuperKEKB-IR



Magnet-cryostats in SuperKEKB-IR



Summary

- KEK has constructed the SuperKEKB accelerator with IR magnets.
  - The target luminosity = 8 $\times 10^{35}$ cm^{-2} s^{-1}
- IR SC magnet system is the most important and complicate hardware in SuperKEKB.
  - The construction of the final focusing system with 8 quadrupoles, 4 compensation solenoids and 43 corrector coils was completed.
  - Commissioning the system and the field measurements were performed from May to August, 2017.
  - From the field measurement results:
    - Some problems were confirmed.
      1. The outer correctors of the QC1RP were assembled with 90 degree rotation to the design.
         - » A_3 corrector -> B_3 corrector
         - » QC1LP and QC1RP have pretty small A_3 components, and then the effects of the function loss is not considered to be crucial.
      2. The iron block for the QC2RE has the multipole fields at the level of 0.2 % of the QC2RE quadrupole field at the surface of this component.
         - » The A_3 field components induced by the iron block for both beams can be handled with the A_3 correctors in the QC2RE and QC2RP quadrupole magnets.